



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Reduction of inorganics from macroalgae *Laminaria digitata* and spent mushroom compost (SMC) by acid leaching and selective hydrothermal liquefaction

Toor, Saqib Sohail; Jasiunas, Lukas; Xu, Chunbao (Charles); Sintamarean, Iulia-Maria; Yu, Donghong; Nielsen, Asbjørn Haaning; Rosendahl, Lasse Aistrup

Published in:
Biomass Conversion and Biorefinery

DOI (link to publication from Publisher):
[10.1007/s13399-017-0290-6](https://doi.org/10.1007/s13399-017-0290-6)

Creative Commons License
Unspecified

Publication date:
2018

Document Version
Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Toor, S. S., Jasiunas, L., Xu, C., Sintamarean, I-M., Yu, D., Nielsen, A. H., & Rosendahl, L. A. (2018). Reduction of inorganics from macroalgae *Laminaria digitata* and spent mushroom compost (SMC) by acid leaching and selective hydrothermal liquefaction. *Biomass Conversion and Biorefinery*, 8(2), 369-377. <https://doi.org/10.1007/s13399-017-0290-6>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Reduction of inorganics from macroalgae *Laminaria digitata* and spent mushroom compost (SMC) by acid leaching and selective hydrothermal liquefaction.

Saqib S. Toor^{1*}, Lukas Jasiunas², Chunbao (Charles) Xu³, Iulia M. Sintamarean¹,
Donghong Yu⁴, Asbjørn H. Nielsen⁵, Lasse A. Rosendahl¹

¹Department of Energy Technology, Aalborg University

²Faculty of Chemical Technology, Kaunas University of Technology, Lithuania

³Department of Chemical and Biochemical Engineering, Western University, Canada

⁴Department of Chemistry and Bioscience, Aalborg University, Denmark

⁵Department of Civil Engineering, Aalborg University, Denmark

Abstract: Hydrothermal liquefaction (HTL) is a promising route for producing bio-crude from various biomass feedstocks. However, high content of inorganic constituents in biomass like macroalgae *Laminaria Digitata* and Spent Mushroom Compost (SMC) affect the conversion process and the resulting fuel products. This research studied the effects of different acid leaching treatments on such feedstocks, subsequent HTL and bio-crude properties. Leaching treatments were performed using five different agents: deionised water, acetic acid, citric acid, sulfuric acid, and hydrochloric acid. Performance of leaching was evaluated by analyzing both leached biomass and HTL products by elemental analysis, ash content, inductively coupled plasma (ICP) analysis, and X-ray diffraction (XRD) analysis. Catalytic and non-catalytic HTL of both feedstocks before and after treatment were performed in 10mL micro reactor at 400°C with holding time of 15 min and pressures (27-30 MPa). For macroalgae, sulfuric acid and hydrochloric acid were found the most effective in reducing the ash content from 30.42% to 20.45% and 20.87%, respectively, followed by acetic and citric acid treatment that could reduce the ash content to 21.5% and 22.15% respectively. Similarly for SMC, citric acid and acetic acid were found the most effective in reducing the ash content from 50.34% to 37.04% and 39.94% respectively. Citric acid did not show significant leaching of organic components such as carbohydrates and proteins, and represented a less toxic and hazardous option for the leaching. The results from HTL of untreated and citric acid treated biomass showed that the acid leaching resulted in an increase in bio-crude yields from 20.7 to 29.2 % (dry ash-free basis) for macroalgae and from 22.9 to 25.1 % for SMC.

Keywords: Hydrothermal liquefaction; inorganic constituents; ash content; acid leaching; bio-crude.

* Corresponding author. Tel.: (+45) 9940 9248

E-mail address: sst@et.aau.dk (Saqib Sohail Toor)

1 Introduction

Depletion of fossil fuel resources and environmental issues associated with greenhouse gases (GHG) are the main reasons increasing the attention towards renewable energy resources like biomass. Various thermochemical technologies can be utilized to convert the biomass into biofuels [1]. Among them, hydrothermal liquefaction (HTL) has received increasing interest in the past decades as a process for converting biomass into drop-in biofuels and chemicals [2-3]. Higher temperatures and pressures to maintain the water as a liquid are generally employed [4]. The biomass feedstock can be processed directly, without an energy-consuming drying step, since water acts both as solvent and catalyst [5-6]. High reactivity and superior ionic product (K_w) of supercritical water break down biomass complex polymers including carbohydrates, lipids, and proteins into smaller molecules that can be converted into bio-crude, water soluble chemicals, solid residue, and gas [4, 7] depending on the catalysts, solvents, feedstock composition, and pretreatment methods employed [8-10].

To avoid negative impacts caused by food production, novel non-food biofuel feedstocks need to be identified and utilised. One option is to utilise marine biomass, notably fast-growing, large marine plants such as macroalgal kelps. Brown macroalgae, *L. Digitata* is considered as the potential biomass source for energy production due to their relatively fast growth rates, ease of harvesting, and low pre-production cost [11]. One of the studies reported the use of *L. Digitata* biomass to generate bio-crude via HTL. They reported a bio-crude yield of 17.6 wt% (daf) basis with a higher heating value (HHV) of 32 MJ/kg [12]. Another study on HTL of brown algae *Saccharina* ssp. reported a yield of 8.7 and 27.7% of bio-crude depending on the harvesting times and conditions of the macroalgae [13]. Spent Mushroom Compost (SMC) is commonly used as a low cost commercial and private scale fertilizer. Approximately 5 kg of SMC is generated from each 1 kg of grown button mushrooms on the farm [14]. That led to ca. 17 million metric tonnes of the byproduct in 2007 globally. In Europe alone, SMC availability is estimated to be 47 million tonnes per year, which results in a potential of ~130 000 tonnes of available feedstock per day [15].

Although HTL has the potential to generate high yields of bio-crude, there are some limitations that need to be addressed if *L. digitata* and SMC to be used as feedstocks. One of the major

limitations is their high ash content (*L. Digitata* up to 30% and SMC up to 50 %). The high ash content is due to the presence of inorganic constituents, mostly alkali and alkaline earth metallic species (AAEMs). This reduces the yield and quality of the generated bio-crude and restricts their alternative usage in direct combustion and gasification processes [9, 16]. Also, physicochemical characteristics of bio-crude can be changed easily during storage due to the presence of higher AAEMs content in the bio-crude, because the AAEMs catalyze the polymerization reactions and thereby increase the viscosity [17]. High ash content can bring additional challenges to the catalytic refining of bio-crude such as decrease in catalyst activities, poisoning, and coking [9, 16]. It is reported that AAEMs present in feedstocks inactivated the catalysts used in the downstream upgrading processes of bio-crude [17-18].

Leaching has been suggested by many authors to be an efficient, fast and low cost way to significantly reduce the ash content of a biomass material [19-21]. Therefore many leaching experiments using different agents such as deionized water [22-23], acetic acid [17, 24], hydrochloric acid [25-26], sulphuric acid [27-28], and citric acid [18] had been conducted.

Post-leaching, water washing steps are carried out in order to remove residual acids. It is well known that alkaline HTL media lead to lower amounts of produced char. Meanwhile, HTL of acidic feedstock slurries ends up generating higher amounts of solid residues. This is believed to be brought on by the fact that low pH media promote dehydration, resulting in the production of easily polymerising unsaturated compounds. HTL of model cellulose shows that acidic conditions lead to lower yields exactly due to the polymerisation of 5-furfural [29]. Neutralisation step via water washing is a welcome alternative especially when strong acids (e.g. hydrochloric acid and sulphuric acid) are used in order to remove chlorine and sulphates which enhance equipment corrosion and fouling in biocrude production and refining, respectively.

In this study, we investigate the impacts of different leaching treatments on both macroalgae *L. Digitata* and SMC biomass. Five different treatments were selected for the study: two strong acids (hydrochloric acid and sulfuric acid), two weak acids (citric and acetic acid), and deionised water. The study focused on analysis of the biomass changes in its physical-chemical composition, and the impact of the pretreatment on the bio-crude yield through the HTL process. The pre-treated and non-treated biomass samples were analyzed and compared for their metal content and organic composition.

2 Materials and Methods

2.1 Raw materials

Macroalgae *L. Digitata* and Spent Mushroom Compost (SMC) biomass were selected for this study. The former was collected from Easdale Island, Scotland and the latter was received from a local Danish mushroom farm (St. Restrup Champignon). The samples were pre-dried at 105 °C for 24 h, pulverized and stored at room temperature for analysis. The particle size fraction of 200µm was used for the experiments.

2.2 Leaching process

L. Digitata and SMC were leached with five different agents for reduction of inorganics: deionised water, acetic acid, citric acid, hydrochloric acid and sulphuric acid, and all acid agents were purchased from Sigma Aldrich, which are in analytical grade of 99.9%. The acids were diluted to 1.0 wt% solutions. In a typical leaching treatment, 10.0 g of biomass were soaked in 100mL of 1.0% acid solution under magnetical stirring (1000 rpm) at 30 °C for 4 h. Lower acid concentration (1.0%) was selected because of lower water consumption for removal of residual acid during post leaching process. After acid leaching, the biomass residues were subjected to water washing in order to eliminate residual acids. The washing was carried out in several steps, each of which consisted of mixing the leached biomass with 200 ml of deionised water, stirring the mixture well and separating the two phases gravimetrically after centrifugation. Treated biomass samples were dried in an electric oven at 105 °C for 24 h, and then stored prior to be used for analyzing. Leaching treatments and analysis were done in triplicate and mean values are reported.

2.3 Biomass characterization methods

2.3.1 Proximate and ultimate analysis

Thermogravimetric analysis (TGA) of treated and untreated biomass samples was applied on Simultaneous Thermal Analyzer (STA) 6000 (PerkinElmer) for determination of moisture, ash, volatile and fixed carbon contents. All samples were heated from 50 to 950 °C at a rate of 10 °C/min under nitrogen atmosphere. Ultimate analysis was carried out by using a vario MACRO cube (Elementar). All the measurements were conducted three times and the mean values are reported.

2.3.2 Inductively coupled plasma- optical emission spectroscopy (ICP-OES)

The alkali and alkaline earth metallic species (AAEMs) of each biomass sample were quantified using inductively coupled plasma-optical emission spectroscopy (ICP-OES) following Microwave Assisted Acid Digestion. The samples were prepared for analysis according to USEPA SW-846 Method 3051A - Microwave Assisted Acid Digestion of Solids and Oils (US. EPA, 2007). The microwave digestion system was an Anton Paar Multiwave 3000 equipped with high-pressure fluoropolymer lined ceramic digestion vessels. The digest of each sample was subsequently diluted to 50.0 mL using type 1 ultra-pure water (PURELAB Ultra, Elga LabWater, Glostrup, Denmark).

The ICP-OES was a Thermo iCap 6300 duo ICP-OES equipped with a Cetac ASX-260 autosampler. The spectrometer was operated in radial view mode with a RF power of 1.15 kW. The plasma and auxiliary gas flows were 12 L min⁻¹ and 1.0 L min⁻¹, respectively. The sample introduction system was a Cetac U5000AT+ ultrasonic nebulizer. The nebulization gas pressure was 0.2 MPa and the sample uptake rate was 2 mL min⁻¹. The ICP-OES was calibrated using matrix matched multi-element external standards (PlasmaCAL, SCP Science, Quebec, Canada). Three standards and one blank were used for calibration of each element using three emission lines. Yttrium was used as internal standard. All standards were traceable to National Institute of Standards and Technology (NIST).

2.3.3 X-ray diffraction analysis

Pretreated and untreated samples of L. Digitata and SMC were analyzed by X-ray diffraction (XRD) analysis on an Empyrean (PANalytical, Netherlands) system under Cu K α radiation ($\lambda=0.1542$ nm; 45kV and 40 mA) in a 2 θ range between 5° and 70° at a step size of 0.013°. The measurements were conducted three times and the mean values are reported.

2.4 Hydrothermal liquefaction methodology

Hydrothermal liquefaction experiments were carried out in a 10 mL stainless steel tubular micro batch reactor at 400 °C and 25-30 MPa with a holding time of 15 minutes. Biomass slurry was prepared with a composition of 85% deionized water, 15% dry biomass, and 5% K₂CO₃ of total biomass (in case of a catalytic run) by weight. In a typical experiment, homogenized biomass slurry (~5 g) was loaded in the reactor and sealed. The system was purged twice to pressures of ~8 Mpa, flushed and finally pressurized to 2±0.1 MPa. The reactor was heated in a

preheated fluidized sand bath (Techne SBL-2D). At the end of the reaction, the reactor was quenched in a cold water bath. Gas products were vented in fume hood. HTL products were separated into bio-crude fraction, water soluble fraction and solid residues according to the procedure schematically shown in Figure 1.

The water phase was poured out of the reactor and filtered using pre-weighed Whatman No. 5 filter paper to collect the solid product. The reactor was washed using acetone (Sigma Aldrich) to recover the biocrude. The acetone and bio-crude mixture was filtered and evaporated using a rotary evaporator to remove the acetone. The solid residue was oven-dried at 105 °C for 24 h. All HTL experiments were performed in triplicates.

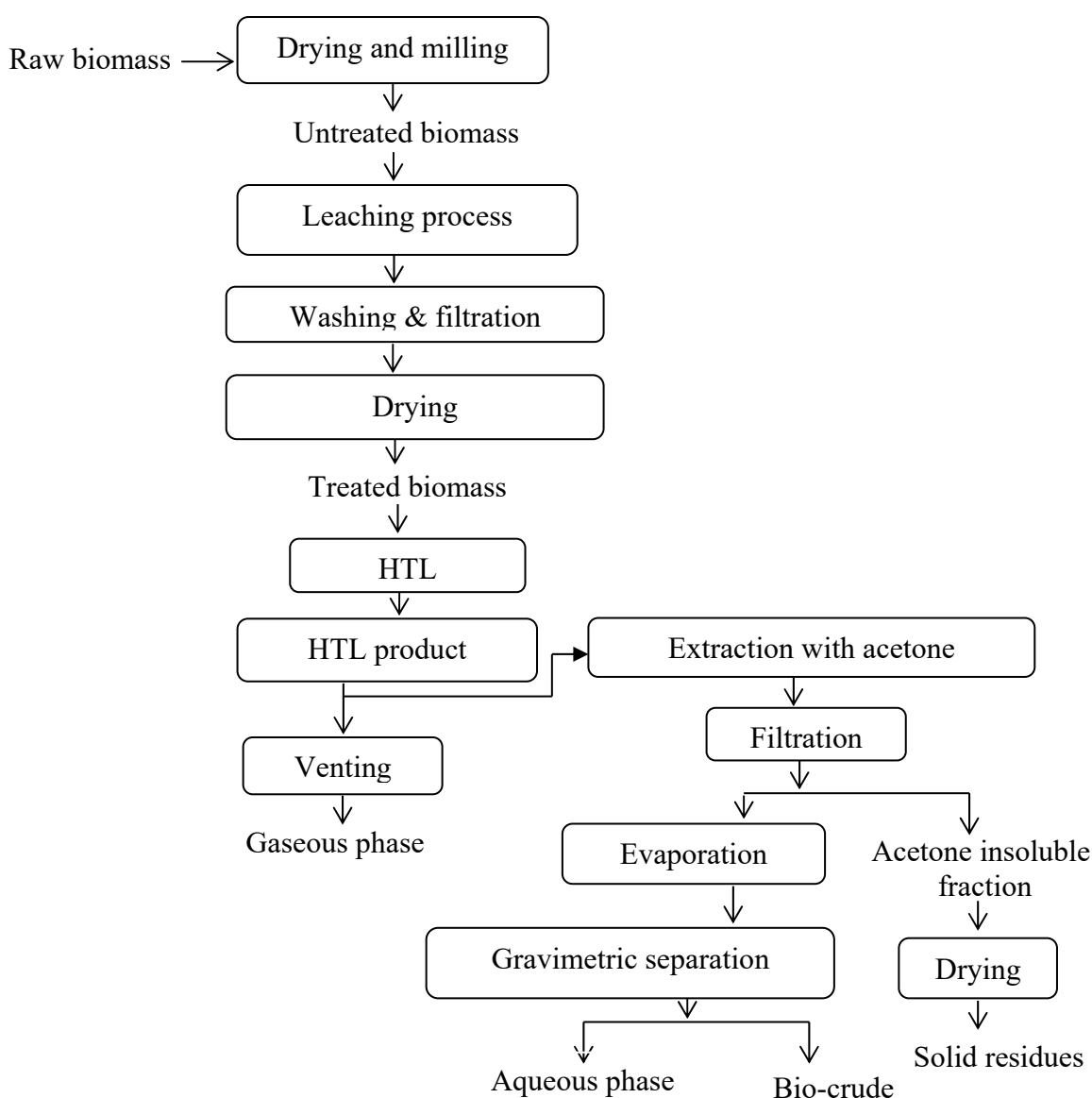


Figure 1. Experimental procedure for biomass leaching and HTL operations.

2.5 Analysis of HTL bio-crude

Bio-crude yield was calculated separately on an ash-and-moisture free basis using the following equation (wt.%) [30]:

$$Y_{bio-crude} (wt. \%) = \left(\frac{W_{biocrude}}{W_{feedstock} - W_{moisture} - W_{ash}} \right) \times 100\% \quad (1)$$

Where, $Y_{bio-crude}$ is the bio-crude yield (wt%) on a dry weight basis, $W_{biocrude}$ is the mass of biocrude (g), $W_{feedstock}$ is the mass of the biomass used in the reactor, $W_{moisture}$ and W_{ash} are the moisture and ash content of the feedstock, respectively. The HHVs of the generated bio-crude were calculated by Channiwala and Parikh formula [31].

$$HHV(MJ / kg) = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211Ash \quad (2)$$

3 Results and Discussions

3.1 Chemical analyses of the samples

The effectiveness of the different biomass leaching treatments was evaluated considering the impact of the treatments on the ash contents of the biomass. The ultimate and proximate analysis results of untreated and treated samples were shown in Table 1.

Table 1 | Proximate analysis of treated and untreated biomasses.

Treatment	Ash (wt%)	Total Moisture (wt%)	VM (wt%)	FC ^a (wt%)	HHV ^b (MJ/kg)
<i>L.digitata</i>					
Untreated	30.42	2.88	49.59	17.11	6.96
Deionized water	28.58	2.1	48.34	20.98	6.60
Acetic acid	21.5	3.91	64.3	10.29	13.93
Hydrochloric acid	20.87	2.46	69.16	7.51	15.83
Sulfuric acid	20.45	2.9	68.47	8.18	14.88
Citric acid	22.15	3.71	64.15	9.99	14.56
Citric acid (5%)	5.96	1.3	75.74	16.99	N/A
<i>SMC</i>					
Untreated	50.34	2.87	36.89	9.9	5.92
Deionized water	47.19	2.89	40.90	9.02	7.34
Acetic acid	39.94	3.27	47.20	9.59	8.93
Hydrochloric acid	41.21	3.38	48.16	7.25	7.53
Sulfuric acid	44.40	2.71	43.75	9.14	6.40
Citric acid	37.04	2.59	49.99	10.38	9.60
Citric acid (5%)	16.66	1.57	67.69	14.06	N/A

^aFixed Carbon obtained by difference between 100% and the sum of ash, moisture, and volatile matter.

^bCalculated by Channiwala and Parikh formula [31]

As shown in Table 1, comparing to the untreated *L. Digitata* sample, the ash content of the deionized water leaching sample decreased from 30.42% in the untreated biomass to 28.58% only, and the ash content of acid leaching samples decreased significantly to 20.45% and even 5.96%, when a 5% citric acid solution was employed. In case of SMC, the ash content of the deionized water leaching sample slightly decreased from 50.34% in the untreated biomass to 47.19%, and the ash content of acid leaching samples decreased to 37.04% and 16.66% with 1% and 5% citric acid solutions, respectively. The ash content of samples decreased remarkably and volatile content increased dramatically after leaching process, which indicates leaching process could improve biomass fuel properties such as heating value. Despite showing similar leaching efficiencies in *L. Digitata* and SMC as 1% solution (27.2% and 26.4%), citric acid performed better in macroalgae when used as a 5% leaching agent (80.4% ash reduction compared to 66.9% in SMC). The fivefold increase in acid concentration led to 3 and 2.5 times higher leaching efficiencies in the two biomass feedstocks, respectively.

As mentioned above, after water leaching, the ash content of *L. Digitata* decreased from 30.42% to 28.58%, hence ~6% are water-soluble ash components. After 1% acid leaching, the ash content of samples decreased to 20.45–22.15%, here the ~27–33% of the lost matter consist of both water-soluble and acid-soluble portions. Similarly, the ash content of SMC decreased from 50.34% to 47.19%, hence ~6% are water-soluble. Whereas after 1% acid solution leaching, the ash content of samples decreased to 37.04–44.40%, here the ~12–26% of the lost mass is composed of both water- and acid-soluble fractions. Considering the ~6% of water-soluble part, the minerals present in the two feedstocks comprise of a significant amount of water-soluble components (mainly in the form of chlorides, nitrates, carbonates and phosphates) [32-33]. The experiments with 5% citric acid solutions, however, showed that stronger acid leaching removes more acid-solubles. Namely, in *L. Digitata*, water-solubles added up to just 7.5% of the total removed ash, while in SMC, the same was true for 9.4% of the removed ash. This confirms the previously described higher efficiency of acid leaching.

The organic components of biomass are composed of different hydrocarbons which mainly consist of C and H atoms. The molecular mass of C is much higher than H, thus the C/H wt% ratio reflects variances in amounts of hydrocarbons. When some hydrocarbons are washed away, the C/H wt% ratio decreases. As shown in Table 2, the C/H wt% ratio of raw and treated samples fluctuates between 7.19 and 7.55 in case of *L. Digitata*, and 7.77 and 9.31 for SMC.

The C/H wt% ratio decreased slightly after the leaching processes, which illustrates that a fraction of organic components were removed from samples during the leaching process. The contents of AAEMs in untreated and treated samples are listed in Table 3. K and Na contents of untreated *L. Digitata* are higher than other metal contents and this is common in brown macroalgae. After distilled water leaching, very small amount of AAEMs were removed, which suggests that the majority of these AAEMs were present in the form of water-insoluble salts. Comparing to water leaching, the amount of AAEMs had different degrees of decline after acid leaching, and such decline was related with acidity of leaching agents. Especially after leaching by strong acids such as HCl and H₂SO₄, more than 90% AAEMs were removed, and, comparing to their reduction by water leaching, it can therefore be deduced that most of AAEMs were present in the form of water-insoluble salts.

Table 2 | Ultimate analysis of treated and untreated biomasses.

Treatment	C (%)	H (%)	N (%)	S (%)	O (%) ^c	C/H ratio
<i>L. digitata</i>						
Untreated	28.23	3.73	2.31	0.98	34.56	7.55
Deionised water	27.23	3.72	2.58	1.06	36.86	7.30
Citric acid	39.66	5.40	3.37	0.83	28.42	7.33
Acetic acid	38.58	5.26	2.63	0.71	30.90	7.32
Hydrochloric acid	40.86	5.63	2.58	0.96	27.74	7.25
Sulfuric acid	38.90	5.40	2.56	0.76	30.28	7.19
<i>SMC</i>						
Untreated	29.14	3.12	1.95	0.48	15.44	9.31
Deionised water	30.20	3.27	1.86	0.31	15.93	9.22
Citric acid	33.09	4.25	2.34	0.45	22.81	7.77
Acetic acid	31.59	4.26	2.32	0.71	21.16	7.39
Hydrochloric acid	29.62	3.88	2.26	0.79	22.23	7.63
Sulfuric acid	28.78	3.41	2.03	0.48	20.88	8.42

^c Obtained by difference between 100% and the wt% of C, H, N, S, and ash.

Table 3 | Alkali and alkaline earth metallic species (AAEMs) of treated and untreated biomasses (mg/g, by dry weight).

Treatment	K	Na	Ca	Mg
<i>L. digitata</i>				
Untreated	92.74	41.74	15.35	9.73
Deionised water	89.81	37.66	17.33	8.57
Citric acid	16.76	6.23	19.72	6.34
Acetic acid	16.64	6.70	21.29	8.62
Hydrochloric acid	4.57	1.54	5.08	1.41
Sulfuric acid	3.66	1.25	4.56	1.08
<i>SMC</i>				
Untreated	18.72	2.22	69.03	3.97
Deionised water	0.8	0.14	67.33	2.87
Citric acid	0.61	0.09	44.13	1.59
Acetic acid	0.63	0.11	42.08	1.68
Hydrochloric acid	0.66	0.10	19.58	1.17
Sulfuric acid	0.60	0.06	34.26	1.28

Ca and K content of untreated SMC is higher than other metal content, while this is not surprising because of excess agricultural fertilization with common gypsum and potash fertilizer during cultivation of mushroom compost. After distilled water leaching, K and Na were almost completely removed comparing to Ca and Mg, which suggests that the majority of K and Na were present in the form of water-soluble salts. After leaching by strong acid such as HCl and H₂SO₄, more than 50 % of Ca and Mg were removed depending upon the acidity of the agents. It means most of Ca and Mg were present in the form of water-insoluble salts. Acid especially strong acid leaching is more effective on removal of AAEMs, but it might introduce a negative impact on physicochemical structure of the samples. Thus as a complementary means of investigation, XRD was used to follow the change of crystalline structures as the leaching agents varied.

3.2 Crystalline structure of treated and untreated biomass

Figure 2 shows changes in the X-ray diffraction pattern of untreated and treated biomass samples.

The diffraction pattern of untreated *L. Digitata* in Figure 2 (a) showed eight peaks of different intensity between 25° and 70° at different 2θ. On diffractograms of the samples after treating with different agents, almost all the peaks disappeared except in case of deionised water

treatment. These results indicated that all the acidic treatments have converted the *L. Digitata* into complete amorphous phases.

In case of SMC, the diffraction pattern of untreated SMC Figure 2 (b) showed numerous peaks of different intensity between 20° and 70° at 2 θ . Almost all the peaks on diffractograms of the samples remained same even after treating with different solvents. So leaching treatments had no impacts on crystallization of the SMC samples.

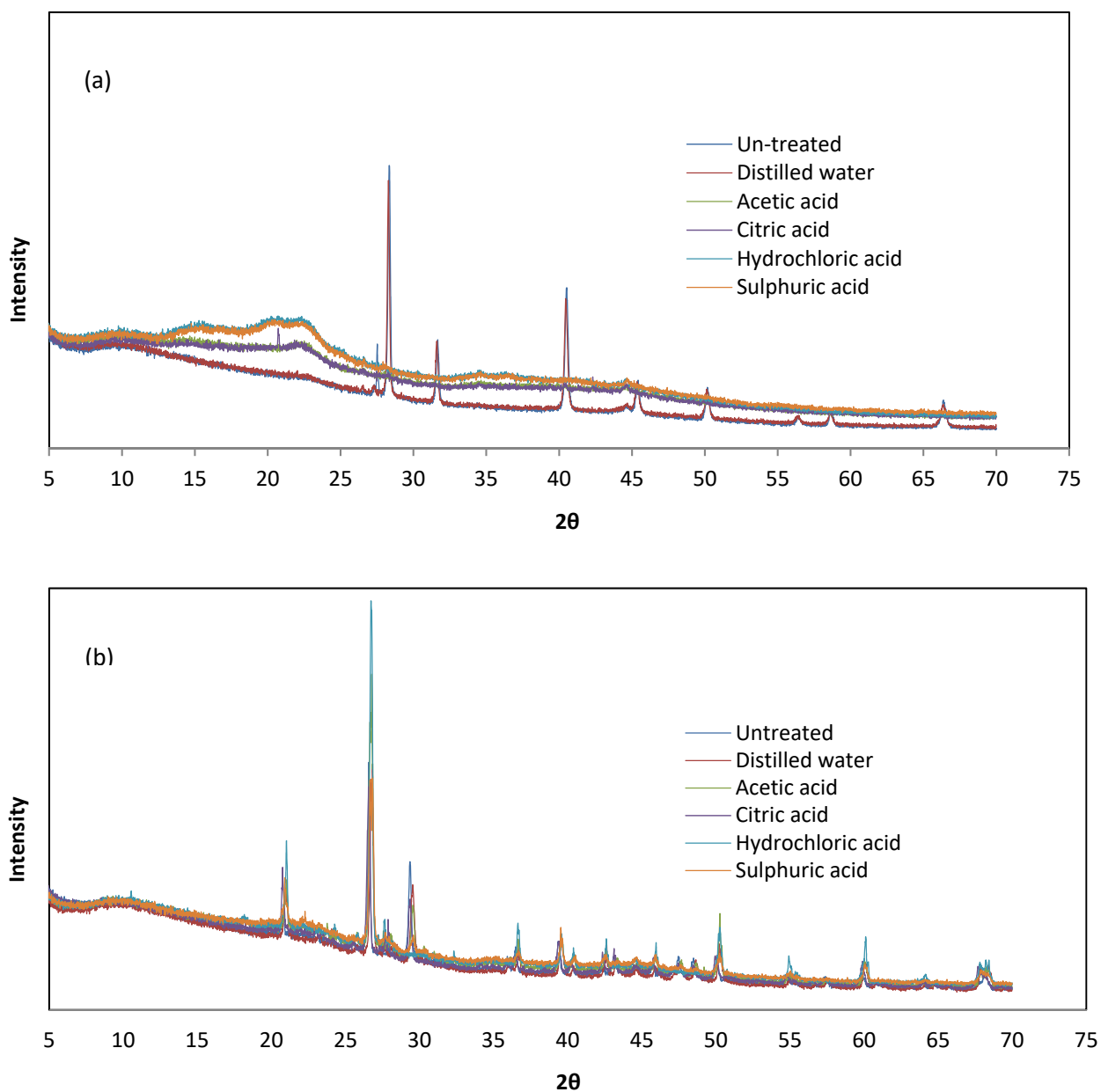


Figure 2. XRD patterns of treated and untreated biomass. (a) *L. Digitata* and (b) SMC.

3.3 Hydrothermal liquefaction of untreated and treated biomass

Although strong acids HCl and H₂SO₄ were better pretreatment agents for leaching both *L. Digitata* and SMC, it could be associated with negative impact on physicochemical structure of the biomass led to the loss of biochemical composition of the biomass. The yield of biocrude in HTL depends on the amount of biochemicals such as carbohydrates, proteins, and lipids present in the biomass. The strong acids were not selected due to their toxicity and also it is very high working load to neutralise the biomass during post-leaching water washing step after the use of strong acids like HCl and H₂SO₄. Although citric acid treatment did not show the highest leaching potential, it was selected for further HTL studies due to its more experimental friendly nature and lower water requirements after post-leaching to neutralise both *L. digitata* and SMC. Proximate analysis of the untreated and treated biomasses (treated with citric acid) was performed and resulted in higher fixed carbon percentage and lower ash content than the untreated one. Also, the citric acid treated biomass had a higher content of volatiles than the untreated biomasses.

3.3.1 HTL products yields

HTL products and yields of citric acid treated and untreated biomasses are presented in Table 4&5.

Table 4 | HTL Products obtained from treated and untreated biomasses.

	Bio-crude (g)	Solid residue (g)	Aqueous phase (g)	Gas phase (g)
<i>L. digitata</i>				
Untreated (non-Cat.)	0.08	0.27	4.29	0.35
Untreated (Cat.)	0.10	0.31	4.15	0.43
Treated with Citric (Cat.)	0.16	0.14	4.33	0.35
<i>SMC</i>				
Untreated (non-Cat.)	0.08	0.44	3.99	0.48
Untreated (Cat.)	0.07	0.42	3.96	0.54
Treated with Citric (non-Cat.)	0.11	0.41	4.25	0.23

Table 5 | HTL Products yields and ash content obtained from treated and untreated biomasses.

	Bio-crude		Solid residue		Ash (wt %)
	Yield ^d (wt%)	St. dev.	Yield ^d (wt%)	St. dev.	
<i>L.digitata</i>					
Untreated (non-Cat.)	16.15	1.73	37.40	0.86	0.12
Untreated (Cat.)	20.69	5.31	42.03	0.99	0.75
Treated with Citric (Cat.)	29.15	2.23	19.89	1.49	0.45
<i>SMC</i>					
Untreated (non-Cat.)	22.86	6.18	58.99	2.95	3.56
Untreated (Cat.)	20.42	7.74	57.42	4.61	0.60
Treated with Citric (non-Cat.)	25.06	0.29	55.14	2.56	4.04

^dDry ash-free (DAF) basis

As anticipated from the proximate analysis, a higher bio-crude yield (29.15%) was obtained from the catalytic HTL of citric acid treated *L. Digitata* than that of untreated through catalytic HTL, which had a bio-crude yield of 20.69%. Similarly in case of SMC, a higher bio-crude yield (25.06%) was obtained from the non-catalytic HTL of citric acid treated SMC than that of untreated SMC through non-catalytic HTL i.e. 22.86%. There are no significant differences in elemental carbon and hydrogen composition in bio-crude samples obtained from both untreated and treated biomasses (Table 6). High oxygen and nitrogen content in bio-crude suggests that an upgrading step is required after the HTL process to convert the product into a drop-in fuel.

Table 6 | Ultimate analysis of biocrude obtained from treated and untreated biomasses.

	C (%)	H (%)	N (%)	S (%)	O (%) ^e
<i>L.digitata</i>					
Untreated (non-Cat.)	76.93	8.57	4.96	0.57	8.83
Untreated (Cat.)	76.04	7.63	4.08	0.60	10.89
Treated with Citric (Cat.)	76.40	8.07	3.92	0.62	10.53
<i>SMC</i>					
Untreated (non-Cat.)	76.39	7.62	3.82	1.01	7.59
Untreated (Cat.)	74.92	7.91	3.17	0.97	12.43
Treated with Citric (non-Cat.)	64.41	7.62	2.77	0.90	20.24

^e Obtained by difference between 100% and the wt% of C, H, N, S and ash.

In summary for the HTL primary fuel target, the bio-crude, we observe an increase in yield and lower ash content, along with decrease in solid residues after the leaching pretreatment.

Although assessing process economics is not among the main objectives of this study, it is necessary to discuss the issues of additional costs and resources associated with feedstock leaching inclusion. Due to low acid concentrations necessary for efficient removal of inorganics, the additional amount of water required for the proposed pre-treatment step is the key factor. The economics of acid leaching are highly dependent on local water availability, water costs and expenses related to process water treatment. Furthermore, costs encountered due to HTL system plugging and fouling are production site specific, namely due to the varying system design and the implemented char evacuation technologies. In the end, case studies shall be carried out to weigh the economic advantages and disadvantages of acid leaching pretreatment for continuous HTL plants.

As far as the results from this study go, the inclusion of feedstock acid leaching is seen as a HTL enabling strategy. The fact that experiments with macroalgae and SMC at batch scale exhibited signs of potential blockage problems (i.e. major agglomeration of solids in the reactor) raise concern for the viability of continuous HTL with such feedstocks. On the other hand, biomass leaching did not lead to decreased bio-crude yields and quality. Given that cheap biomass often has a low calorific value, is of high humidity and exhibits a high content of inorganics, system blockages are the major obstacle for large scale continuous HTL processing. Waste biomass valorisation via HTL is known for its high energetic efficiency [34] and the capacity to produce high quality biofuel precursors. The possibility of successfully converting low-cost high-ash sustainable feedstocks might as well lead to enabling acid leaching as an additional pretreatment step.

3.4 Water demand for biomass neutralisation

Water demand was quantified for each leaching procedure with the two studied feedstocks. In the case of *L. digitata*, the acetic and citric acid leached biomass reached neutral pH after 6 washing steps, whereas algae exposed to hydrochloric and sulphuric acid leaching remained at pH 5 and 4, respectively, even after 8 washing steps. Acetic, citric and sulphuric acid leached SMC reached neutral pH already after 3 washing steps, whereas hydrochloric acid pretreated biomass remained at pH 5 after 8 consecutive washing steps. Here, 3, 6 and 8 washing steps signify process water consumption levels of 0.06, 0.12 and 0.16 L for each gram of initial feedstock.

Water washing as a post acid leaching neutralisation technique inherently increases process water demands hence future facilities must take this and the raised subsequent waste water treatment requirements into account when carrying out techno-economic analyses of continuous HTL processing. HTL specific research is needed on the alternative chemical neutralisation route. Acid neutralisation via the addition of bases is a straightforward reaction chemically, however the acidic and basic compounds present in the feedstock might have adverse effects on the production of biocrude due to precipitation, especially in terms of potentially impaired yields and promoted formation of solids. Arguably, when comparing water and chemical neutralisation, the effect of superior organic matter preservation might counteract the possible drop in biocrude yields caused by acid driven recondensation reactions.

4 Conclusions

The effects of leaching pretreatments using five different leaching agents (deionised water, acetic acid, citric acid, sulfuric acid, and hydrochloric acid) on HTL of *L. Digitata* and SMC biomass were studied. It was found that all the leaching pretreatments decreased the inorganic contents in the biomasses as expected. While, citric acid was selected as the best leaching agent because it was able to remove maximum AAEMs without using a large amount of water in the post leaching process to neutralize the biomasses. In addition, it represents a more eco-friendly alternative. The results of HTL of both treated and untreated *L. Digitata* and SMC showed that the leaching treatment resulted in an increase in bio-crude yield from 20.7 to 29.2 % (dry ash-free basis) for macroalgae and from 22.9 and 25.1 % for SMC.

Acknowledgements

This work is part of C3BO (Center for BioOil) at the Department of Energy Technology, Aalborg University. The research was financially supported by a grant from the Innovation Fund Denmark Grant No 1305-00030B. Authors are grateful to Patrick Biller and Maika Klemmer from Department of Chemistry, Aarhus University for their support with some of the analysis. One of the authors Chunbao (Charles) Xu would also like to acknowledge the VELUX Visiting Professor Programme.

References

[1] M. Asadieraghi, WMAW. Daud, Characterization of lignocellulosic biomass thermal degradation and physiochemical structure: Effects of demineralization by

- diverse acid solutions, *Energy Convers. And Mgmt.* 82 (2014) 71–82.
- [2] P. Biller, A.B. Ross, Hydrothermal processing of algal biomass for the production of biofuels and chemicals, *Biofuels.* 3 (2012) 603–623.
- [3] D. L. Barreiro, W. Prins, F. Ronsse, W. Brilman, Hydrothermal liquefaction (HTL) of microalgae for biofuel production: state of the art review and future prospects, *Biomass Bioenergy.* 53 (2013) 113–127.
- [4] S.R. Villadsen, L. Dithmer, R. Forsberg, J. Becker, A. Rudolf, S.B. Iversen, B.B. Iversen, M. Glasius, Development and application of chemical analysis methods for investigation of bio-oils and aqueous phase from hydrothermal liquefaction of biomass, *Energy & Fuels.* 26 (2012) 6988–6998.
- [5] S.S. Toor, L. Rosendahl, A. Rudolf, Hydrothermal liquefaction of biomass: a review of subcritical water technologies, *Energy.* 36 (2011) 2328–2342.
- [6] C. Jazrawi, P. Biller, Y. He, A. Montoya, A. B. Ross, T. Maschmeyer, B.S. Haynes, Two-stage hydrothermal liquefaction of a high-protein microalga, *Algal Research.* 8 (2015) 15–22.
- [7] A.A. Peterson, F. Vogel, R.P. Lachance, M. Fröling, M.J.Jr. Antal, J.W. Tester, Thermochemical biofuel production in hydrothermal media: a review of sub- and supercritical water technologies, *Energy Environ.Sci.* 1 (2008) 32–65.
- [8] Y. Zhuang, J. Guo, L. Chen, D. Li, J. Liu, N. Ye, Microwave-assisted direct liquefaction of *Ulva prolifera* for bio-oil production by acid catalysis, *Bioresour.Technol.* 116 (2012) 133–139.
- [9] N. Neveux, A.K. Yuen, C. Jazrawi, M. Magnusson, B.S. Haynes, A.F. Masters, A. Montoya, N.A. Paul, T. Maschmeyer, R. de Nys, Biocrude yield and productivity from the hydrothermal liquefaction of marine and fresh water green macroalgae, *Bioresour.Technol.* 155 (2014) 334–341.
- [10] R. Singh, T. Bhaskar, B. Balagurumurthy, Effect of solvent on the hydrothermal liquefaction of macroalgae *Ulva fasciata*, *Process Saf. Environ. Prot.* 93 (2015) 154–160.
- [11] J.M.M. Adams, A.B. Ross, K. Anastasakis, E.M. Hodgson, J.A. Gallagher, J.M. Jones, I.S. Donnison, Seasonal variation in the chemical composition of the bioenergy feedstock *Laminaria digitata* for thermochemical conversion, *Bioresource Technology.* 102 (2011) 226–234.
- [12] K. Anastasakis, A.B. Ross, Hydrothermal liquefaction of four brown macro-algae commonly found on the UK coasts: An energetic analysis of the process and comparison with bio-chemical conversion methods, *Fuel.* 139 (2015) 546–553.
- [13] D. C. Elliott, T. R. Hart, G.G Neuenschwander, L.J. Rotness, G. Roesijadi, A.H. Zacher, J.K. Magnuson, Hydrothermal processing of macroalgal feedstocks in continuous-flow reactors, *ACS Sustain.Chem.Eng.* 2(2) (2013) 207–215.

- [14] B. C. Williams, J. T. McMullan, S. McCahey, An initial assessment of spent mushroom compost as a potential energy feedstock, *Bioresource Technology*. 79 (3) (2001) 227-230.
- [15] Eurostat, Mushrooms, energy crops, GMO: number of farms and areas by size of farm (UAA), 2005-2013 data, Tech. rep. (2016-09-15).
- [16] Q. V. Bach, M.V. Sillero, K.Q. Tran, J. Skjermo, Fast hydrothermal liquefaction of a Norwegian macroalga: screening tests, *Algal Res.* 6 (PtB) (2014) 271–276.
- [17] X. Liu, X.T. Bi, Removal of inorganic constituents from pine barks and switchgrass, *Fuel Process. Technol.* 92 (2011) 1273–1279.
- [18] L.M.D. Vázquez¹, A.R. Pérez, M.F. Caraballo, I.V. Robles, U. Jena, K.C. Das, Demineralization of *Sargassum* spp. Macroalgae biomass: selective hydrothermal liquefaction process for bio-oil production, *Frontiers in Energy Research*. 3 (2015) 1-11.
- [19] B.M. Jenkins, R.R. Bakker, J.B. Wei, On the properties of washed straw, *Biomass and Bioenergy*. 10 (4) (1996) 177–200.
- [20] S.Q. Turn, C.M. Kinoshita, D.M. Ishimura, Removal of inorganic constituents of biomass feedstocks by mechanical dewatering and leaching, *Biomass and Bioenergy*. 12 (4) (1997) 241-252.
- [21] L. Jiang, S. Hu, L. Sun, S. Su, K. Xu, L. He, J. Xiang, Influence of different demineralization treatments on physicochemical structure and thermal degradation of biomass, *Bioresource Technology*. 146 (2013) 254–260.
- [22] R. Fahmi, A. Bridgwater, I. Donnison, N. Yates, J.M. Jones, The effect of lignin and inorganic species in biomass on pyrolysis oil yields, quality and stability, *Fuel*. 87 (2008) 1230–1240.
- [23] D. Maurant, Z.H. Wang, M. He, X.S. Wang, M. Garcia-Perez, K.C. Ling, C.Z. Li, Mallee wood fast pyrolysis: effects of alkali and alkaline earth metallic species on the yield and composition of bio-oil, *Fuel*. 90 (2011) 2915–2922.
- [24] K.O. Davidsson, J.G. Korsgren, J.B.C. Pettersson, U. Jaglid, The effects of fuel washing techniques on alkali release from biomass, *Fuel*. 81 (2002) 137–142.
- [25] I.Y. Eom, K.H. Kim, J.Y. Kim, S.M. Lee, H.M. Yeo, I.G. Choi, J.W. Choi, Characterization of primary thermal degradation features of lignocellulosic biomass after removal of inorganic metals by diverse solvents, *Bioresour. Technol.* 102 (2011) 3437–3444.
- [26] Z.A. Mayer, A. Apfelbacher, A. Hornung, Effect of sample preparation on the thermal degradation of metal-added biomass, *J. Anal. Appl. Pyrolysis*. 94 (2012) 170–176.

- [27] V. Fierro, V. Torne-Fernandez, A. Celzard, D. Montane, Influence of the demineralisation on the chemical activation of Kraft lignin with orthophosphoric acid, *J. Hazard. Mater.* 149 (2007) 126–133.
- [28] D.M. Keown, J.I. Hayashi, C.Z. Li, Effects of volatile–char interactions on the volatilisation of alkali and alkaline earth metallic species during the pyrolysis of biomass, *Fuel*. 87 (2008) 1187–1194.
- [29] S. Yin, Z. Tan, Hydrothermal liquefaction of cellulose to bio-oil under acidic, neutral and alkaline conditions, *Applied Energy*. 92 (2012) 234–239.
- [30] D. Li, L. Chen, D. Xu, X. Zhang, N. Ye, F. Chen, S. Chen, Preparation and characteristics of bio-oil from the marine brown alga *Sargassum patens* C. Agardh, *Bioresource Technology*. 104 (2012) 737–742.
- [31] S.A. Channiwala, P.P. Parikh, A unified correlation for estimating HHV of solid, liquid and gaseous fuels, *Fuel*. 81 (8) (2002) 1051–1063.
- [32] J.N. Knudsen, P.A. Jensen, K. Dam-Johansen, Transformation and release to the gas phase of Cl, K, and S during combustion of annual biomass, *Energy Fuels*. 18 (2004) 1385–1399.
- [33] P.R. Patwardhan, J.A. Satrio, R.C. Brown, B.H. Shanks, Influence of inorganic salts on the primary pyrolysis products of cellulose, *Bioresour. Technol.* 101 (2010) 4646–4655.
- [34] W. Feng, H. J. van der Kooi, J. D. S. Arons, Biomass conversions in subcritical and supercritical water: driving force, phase equilibria, and thermodynamic analysis, *Chemical Engineering and Processing*. 43 (2004) 1459–1467.